REMARKS

Applicants amend claims 1, 24 and 25, and add new claims 27 and 28. Support for the amendments and the new claims can be found, e.g., on pages 3, 11 and 13, in original claims, and throughout the remainder of the specification. No new matter is added. Prior to discussing the various grounds of rejection in detail, the salient aspects of the claimed invention and their distinctions from the prior art will be discussed.

The present invention is generally directed to quantum cascade (QC) lasers that operate in a frequency range of about 1 to about 10 Terahertz. The QC lasers include a plurality of lasing modules that are connected in series. Each lasing module comprises a plurality of quantum well structures that collectively generate an upper lasing state, a lower lasing state, and a relaxation state. The wavefunction of these states are designed such that the upper and lower lasing states exhibit a differential non-radiative relaxation rate into the relaxation state, via emission of resonant LO-phonons, while at the same time exhibiting a strong radiative coupling, i.e., a strong radiative lasing transition. The combination of these two properties, i.e., a differential coupling of the two lasing states to the relaxation state and a strong radiative coupling between the lasing states, results in enhanced properties of the QC lasers of the invention. For example, they can operate at much higher temperatures, e.g., at temperatures greater than about 87 K. These features can be further appreciated by considering the following Figure 1 that schematically shows the wavefunctions characterizing the upper and lower lasing states (5 and 4, respectively), as well as the relaxation state (1), of an exemplary QC laser in accordance with one embodiment of the invention.

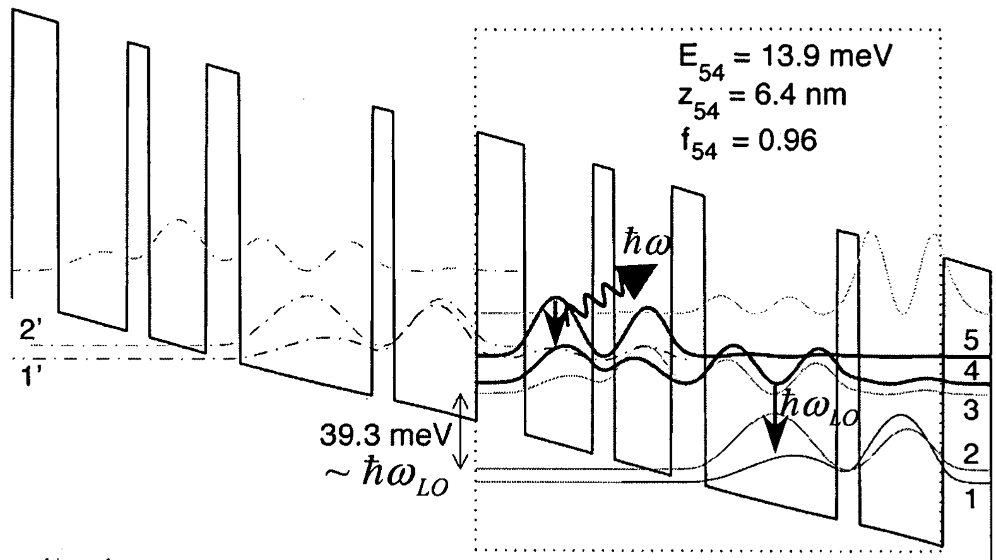

Fig. 1

As evident in the above band diagram, the wavefunctions of the upper and the lower lasing states (i.e., states 5 and 4) have significant overlap in two of the quantum wells of each lasing module. This overlap leads to an enhanced radiative coupling between those lasing states. Further, while both the lower lasing state and the relaxation state have appreciable values in a third quantum well, the wavefunction of the upper lasing state substantially vanishes in that well. In other words, the lower lasing state exhibits a much better phonon coupling with the relaxation state than that of the upper lasing state. This differential coupling, in turn, allows a much more efficient operation of the laser by facilitating creation of a population inversion between the lasing states.

In contrast, in prior art lasers, differential coupling of the lasing states to the relaxation state is obtained at the expense of radiative coupling between those lasing states. Alternatively, a reasonable radiative coupling between the lasing states is obtained at the expense of decreasing the difference in the coupling of the upper and the lower lasing state to the relaxation state. Applicants have, however, discovered how to design QC lasers that exhibit not only good differential coupling between the lasing states and a relaxation state but also a strong radiative coupling between the lasing states.

The prior art references cited by the Examiner do not provide the combination of the above two properties of QC lasers of the invention. For example, the following diagram schematically shows the wavefunctions associated with the upper, the lower and the relaxation states of a QC laser similar to that disclosed in the article entitled "Electrically pumped tunable terahertz emitter based on intersubband transition," authored by Xu and Hu:

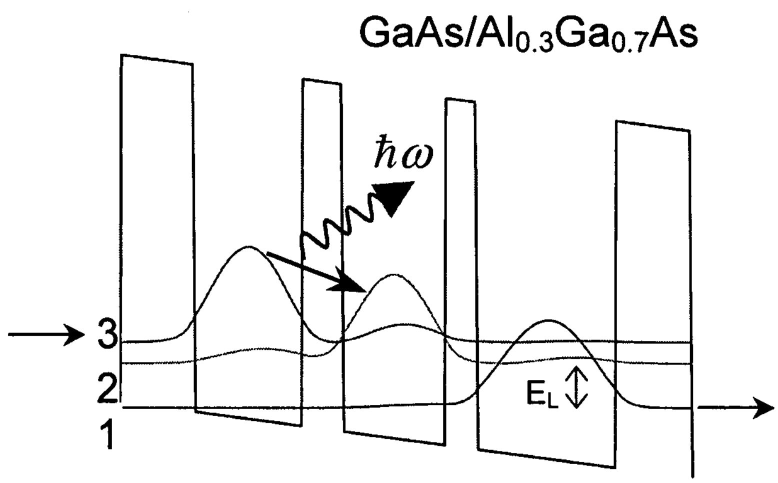

Fig. 2

An inspection of this diagram shows that although the wavefunctions of the upper and the lower lasing states are differentially coupled to that of the relaxation state, no strong radiative coupling exists between the two lasing states. More specifically, the wavefunction associated with the upper lasing state has an appreciable value in one of the quantum wells while the wavefunction associated with the lower lasing state has an appreciable value in a different (an adjacent) quantum well. In other words, the spatial overlap between these two wavefunctions is not strong, leading to a weak radiative transition therebetween. That is, the upper and the lower lasing states do *not* exhibit a *spatially vertical* radiative transition, i.e., one involving transitions within the same quantum well rather than between adjacent quantum wells.

In the QC laser described in the article "Narrow-linewidth terahertz intersubband emission from three-level systems" of Williams et al., the two lasing states exhibit a greater radiative coupling than that exhibited by the lasing states of the above QC laser of

Xu *et. al.* However, the lasing states do not exhibit a large difference in their couplings to the relaxation state. This can be better understood by considering the following band diagram of a QC laser similar to that disclosed in Williams:

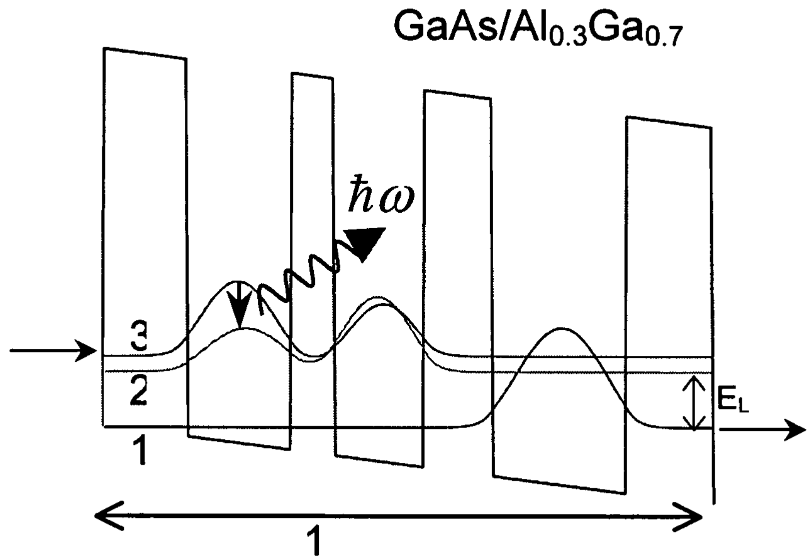

Fig. 3

As can be seen in the band diagram of Figure 3, although the wavefunctions of the two lasing states (i.e., states 3 and 2) have both appreciable values in the two wells of the three quantum wells comprising the depicted lasing module, neither has any appreciable value in the third well in which the wavefunction of the relaxation state (E1) is concentrated.

Accordingly, the claimed QC lasers present a significant advance over the conventional QC lasers in that they not only provide strong radiative coupling between the lasing states, but also a large degree of difference in the phonon coupling of the upper lasing state to a relaxation state relative to a corresponding coupling of the lower lasing state to the relaxation state.

The specific rejections will now be discussed in view of the above description of the prior art and the invention.

Rejections Under 35 U.S.C. 102

The Office Action rejects claims 1, 5-8, 13, 16-17 and 22-24 as being anticipated by the afore-mentioned article of Xu *et al.*

Claim 1, as amended, recites a quantum cascade laser that comprises a semiconductor heterostructure providing a plurality of lasing modules connected in series. Each lasing module comprises a plurality of quantum well structures collectively generating at least an upper lasing state, a lower lasing state, and a relaxation state such that the upper and lower lasing states are separated by an energy corresponding to an optical frequency in a range of about 1 to about 10 Terahertz and such that a radiative lasing transition between said upper lasing state and said lower lasing state is *spatially vertical.* The electrons populating the lower lasing state exhibit a non-radiative relaxation via resonant emission of LO-phonon into the relaxation state. The resonant LO-phonon emission selectively depopulates the lower lasing state such that *a ratio of a lifetime of said upper lasing state relative to lifetime of said lower lasing state is at least about 5.*

Support for amendments to claim 1 can be found on pages 3, 11, and 13, in original claims (e.g., 8), and throughout the remainder of the specification.

As noted above, in Xu's QC laser, the transition between the upper and the lower lasing states is not spatially vertical. In other words, a radiative transition between the upper and the lower lasing states in Xu does not involve an electronic transition within the same quantum well. Rather, it involves an electronic transition between *adjacent* quantum wells. This is evident in the band diagram of Xu's QC laser, shown schematically in Figure 2 above: the wavefunctions of the upper and lower lasing states are concentrated in different quantum wells and exhibit vanishing overlap in any common quantum well.

In contrast, claim 1 recites that a radiative transition between the upper and lower lasing states is spatially vertical. For example, in the band diagram of an embodiment of a QC laser of the invention shown in the above Figure 1, the wavefunctions of both the upper and the lower lasing states exhibit substantial values in common quantum wells.

The spatially vertical radiative transition between the upper and the lower lasing states (in other words, enhanced radiative coupling between those two states) in the claimed QC laser provides distinct advantages over the QC laser of Xu. For example, such enhanced coupling between the lasing states results in a much more efficient operation of the laser.

Accordingly, claim 1 distinguishes patentably over the cited art. Further, claim 5-8, 13,16-17, 22 and 23 depend, either directly or indirectly, on claim 1, and hence are also patentable.

The arguments presented above apply with equal force to establish that amended claim 24 also distinguishes over Xu. In particular, amended claim 24 recites that the upper and lower amplification states exhibit a spatially vertical radiative transition – a feature not taught by Xu.

The Office Action rejects claim 1 and claims 9-10 as being anticipated by the afore-mentioned article of Williams et al. entitled "Narrow-linewidth terahertz intersubband emission from three-level systems."

Williams does not each or suggest a difference between the relaxation rate of the upper lasing and the lower lasing states of its QC laser into a relaxation state that would result in *a ratio of at least about 5 for a lifetime of the upper lasing state relative to that of the lower lasing state*. In other words, Williams fails to teach the high differential coupling of the upper and the lower lasing states of the claimed QC to the relaxation state: a differential coupling characterized by a rate of phonon-mediated transitions from

the lower lasing state into the relaxation state that is at least about 5 times higher than the corresponding rate associated with the upper lasing state.

The enhanced differential coupling between the upper and the lower lasing states of the claimed QC – while maintaining a good radiative coupling between the lasing states – provides a number of advantages not achieved by the QC laser of Williams, such as the capability to operate at much higher temperatures.

Accordingly, claim 1 and claims 9-10, which depend directly and indirectly on claim 1, distinguish patentably over Williams.

The Office Action rejects claims 1, 14-15 and 21 as being anticipated by Kohler *et al*'s article entitled "Terhertz Semiconductor heterstructure Laser."

Although Kohler is generally related to a terahertz injection laser, it does not teach or suggest the salient features of claim 1: a terahertz laser that exhibits not only a *spatially vertical radiative transition* between its upper and lower lasing states but also a sufficient difference in the phonon-mediated coupling of the two lasing states to a lower-lying relaxation state that results in at least a *factor of 5 difference in the lifetimes* of those lasing states.

Hence, independent claim 1, and claims 14-15 and 21 that depend on claim 1, are patentable over Kohler.

Claims 1, 2 and 25-26 stand rejected as being anticipated by published U.S. Patent Application No. 2003/0219052 of Goodhue.

Goodhue is generally directed to semiconductor heterostructure light emitting devices. Unlike amended claim 1, Goodhue does not teach a QC laser in which the upper and the lower lasing states exhibit a spatially vertical radiative transition. On the

contrary, Goodhue asserts that its quantum cascade structures "rely on *spatially diagonal* (interwell) transition for the terahertz emission." [Emphasis added] *See*, Goodhue, page 2, paragraph 18.

The Examiner refers to paragraph 264 of Goodhue to assert that in some embodiments, Goodhue's structures exhibit a phonon-mediated differential relaxation into a relaxation state that results in a ratio of lifetimes of at least about 10 for the two lasing states. Applicants respectfully disagree for the following reasons. This passage of Goodhue relates to a four level structure characterized by levels |1>, |2>, |3> and |4>. Goodhue states that, in some embodiments, the phonon-limited lifetime of level |2> is about 0.8 ps. It further asserts that the lifetime of the |3> and |4> levels at low operating temperatures is dominated by *electron-electron* (e-e) interactions and is predicted to be about 10 ps. In other words, this passage of Goodhue is not direct to *phonon-mediated* lifetimes of two lasing states into a relaxation state. Rather, the lifetime estimate provided for the levels |3> and |4> are based on the assumption that "e-e intraction is the most dominant non-radiative mechanism." In contrast, amended claim 1 recites that the relaxation of the lower lasing state into the relaxation state is via resonant emission of LO-phonons.

In sum, Goodhue fails to each the salient features of claims 1, and those of claim 2 that depends on claim 1. Further, similar arguments apply to establish that amended claim 25 distinguishes over Goodhue. In particular, Goodhue teaches neither vertical transitions between the lasing states nor a differential rate of at least about 5 for phonon-mediated relaxation of the lasing states into a relaxation state -- features recited in claim 25. As claim 26 depends on claim 25, that claim is also patentable over Goodhue.

<u>Rejections Under 35 U.S.C. 103</u>

Claims 3-4 are rejected as being obvious over Xu in view of an article entitled "High performance interminiband quantum cascade lasers with graded superlattice," authored by Tredicucci *et al.*

Claim 3 depends on claim 1, and further recites that the laser generates lasing radiation at an operating temperature above about 87 K. Similarly, claim 4 depends on claim 1, and further recites that the laser generates lasing radiation at an operating temperature above about 130 K.

As discussed above, Xu fails to teach the features of claim 1, and consequently those of claims 3 and 4 that depend on claim 1. Tredicucci fails to cure the shortcomings of Xu. As an initial matter, Tredicucci is directed to infrared lasers and not terahertz lasers that operate in a range of about 1 to about 10 THz. For example, whereas Tredicucci discloses a QC laser that operates at 7.6 micron, the claimed QC lasers operate at much longer wavelengths of about 30 to about 300 microns (i.e., a frequency range of about 1 to about 10 THz). As such, the teachings of Tredicucci regarding the temperatures at which its lasers can operate are not pertinent to the claimed THz QC lasers. More specifically, the claimed QC lasers operate in a much longer wavelength region in which the energy spacing between the lasing states are much smaller. In fact, there is a qualitative difference between Tredicucci's laser and the THz QCLs desribed in this application. While the energy spacing in the former is greater than the energy of LO-phonon, the energy spacing in the latter is smaller than the LO-phonon energy, thus rendering the creation of population inversion between those states considerably more challenging, especially at temperatures above cryogenic temperatures.

The Examiner states that it would have been obvious to combine the cascade lasers of Xu with the operating temperatures of Tredicucci to provide the claimed terahertz laser. Applicants respectfully disagree. As noted above, the teachings of Tredicucci are not applicable to terahertz lasers. And more generally, the fact that lasers operating at a particular temperature are available in a given frequency regime has little bearing on whether similar operating temperatures can be achieved for lasers operating at a significantly different frequency regime.

Accordingly, claims 3 and 4 distinguish patentably over the combined teachings of Xu and Tredicucci.

The Office Action rejects claims 11-12 as being obvious over Xu in view of Faist *et al.*'s article entitled "Bound-to continuum and two-phonon resonance quantum-cascade lasers for high duty cycle, high-temperature operation."

Claims 11 and 12 depend indirectly on claim 1, and hence incorporate the features of that claim. As discussed in detail above, Xu fails to teach the salient features of claim 1 (and consequently those of claims 11 and 12). And Faist does not cure the shortcomings of Xu in that it does not teach QC lasers operating in a frequency range of about 1 to about 10 THz in which two lasing states of each module not only exhibit a strong radiative coupling but also a large differential phonon coupling with a lower-lying relaxation state.

Thus, claims 11-12 are patentable over the cited art.

Claims 18-20 are rejected as being obvious over the teachings of Xu in view of those of Unterrainer.

Claim 18 depends on claim 1, and further recites a waveguide coupled to the semiconductor heterostructure for confining selected lasing modes of the laser. Claim 18 depends on claim 19 and recites that the waveguide is formed of a metallic layer and a heavily doped semiconductor layer between which the semiconductor heterostructure is sandwiched. And claim 20, as amended, depends on claim 18 and recites that waveguide is formed of two metallic layers between which the semiconductor heterostructure is sandwiched.

As discussed in detail above, Xu does not teach the features of claim 1, and consequently those of claims 18-20. And Unterrainer does not cure the shortcomings of

Xu in this regard. As an initial matter, Unterrainer is directed to QC lasers that operate at much shorter wavelengths than those at which the claimed QC operate. Furthermore, similar to Xu, Unterrainer fails to teach the salient features of claim 1 (and hence those of claims 18-20).

Double Patenting Rejections

Claims 1, 8, 13-14, 16-20 and 24-25 are provisionally rejected based on obviousness-type double patenting over claims 1, 9-14 and 18 of co-pending Patent Application No. 10/661832.

In response, Applicants file the attached Terminal Disclaimer to overcome these rejections.

New Claims

New independent claim 27 recites a quantum cascade laser, which comprises a semiconductor heterostructure providing a plurality of lasing modules connected in series. Each lasing module comprises a plurality of quantum well structures that collectively generate at least an upper lasing state, a lower lasing state, and a relaxation state such that the upper and the lower lasing states are separated by an energy corresponding to an optical frequency in a range of about 1 to about 10 Terahertz. The electrons populating the lower lasing state exhibit a non-radiative relaxation via resonant emission of LO-phonons into the relaxation state. The laser is capable of generating lasing radiation at operating temperatures above about 87 K.

Support for claim 27 can be found, e.g., in the original claims (e.g., claims 1 and 3), and throughout the remainder of the specification.

The arguments presented above also establish that claim 27 is also patentable over the cited art. In particular, none of the cited references teaches a QC laser generating lasing radiation in a frequency range of about 1 to about 10 THz that is capable of

operating at temperatures above about 87 K. Moreover, as noted above, the existence of lasers in significantly different frequency ranges that operate at temperatures above 87 in no way suggests how to fabricate a laser in the claimed frequency range that operates at those temperatures.

New independent claim 28 recites a quantum cascade laser, which comprises a semiconductor heterostructure providing a plurality of lasing modules connected in series. Each lasing module comprises a plurality of quantum well structures collectively generating at least an upper lasing state, a lower lasing state, and a relaxation state such that the upper and lower lasing states are separated by an energy corresponding to an optical frequency in a range of about 1 to about 10 Terahertz, and the upper and lower lasing state exhibit a radiative oscillator strength of about unity. The electrons populating the lower lasing state exhibit a non-radiative relaxation via resonant emission of LO-phonon into the relaxation state. The resonant LO-phonon emission selectively depopulates the lower lasing state such that a ratio of a lifetime of said upper lasing state relative to lifetime of said lower lasing state is at least about 5.

Support for claim 28 can be found, e.g., on pages 3 and 13, paragraph 48 of the specification, in the original claims, and throughout the remainder of the specification.

The cited references do not teach a QC laser operating in the claimed frequency range exhibiting a radiative coupling between its lasing states characterized by a coupling constant of about unity, and concurrently a differential phonon-mediated lifetime of at least about 5 between those lasing states.

Conclusion

In view of the above amendments and remarks, Applicants respectfully request reconsideration and allowance of the application. Applicants invite the Examiner to call the undersigned at (617) 439-2514 if there are any remaining questions.

Dated: January 10, 2006

Respectfully submitted,

By________________________

Reza Mollaaghababa
Registration No.: 43,810
NUTTER MCCLENNEN & FISH LLP
World Trade Center West
155 Seaport Boulevard
Boston, Massachusetts 02210-2604
(617) 439-2514
(617) 310-9514 (Fax)
Attorney for Applicant

1483555.1